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**SCATTERING AND DEPOLARIZATION  
BY IRREGULAR LAYERED MEDIA FULL WAVE SOLUTIONS**

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## PREFACE

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# SCATTERING AND DEPOLARIZATION BY IRREGULAR LAYERED MEDIA FULL WAVE SOLUTIONS

## 1 Introduction and Overview

Rigorous closed form solutions for the reflection and transmission of electromagnetic waves have been derived for multilayered dielectric structures of uniform thickness. However, in a large variety of pertinent radio wave propagation problems the thickness of the layers are nonuniform and the height of the interface between two adjacent dielectric layers is a random function. In these cases the incident waves are depolarized and scattered into both propagating and evanescent waves. Furthermore, an incident plane wave may be coupled into guided surface waves and lateral waves of the structure.

Often the problem that is actually solved is a highly idealized version of the original problem and concepts such as "effective dielectric coefficient" and "effective surface impedance" are introduced in order to make the solution of the original problem more tractable. However, the validity of such approximations is very limited and often questionable and they do not necessarily satisfy reciprocity.

Using a full wave approach, it is possible to analyze more realistic models of the original physical structure without introducing simplifying approximations that cannot be justified a priori. The full wave approach is based on the expansion of the electromagnetic fields into a complete spectrum of vertically and horizontally polarized (propagating and evanescent) waves that include the radiation term, the lateral wave and the guided (surface) waves of the structure. Exact boundary conditions are imposed at each irregular interface of the structure and Maxwell's equations are converted into a rigorous set of coupled telegraphists' equations. To this end, precise mathematical procedures are followed and term by term differentiation of nonuniform convergent series is avoided. The coupled telegraphists' equations provide solutions for the forward and backward traveling complex wave amplitudes that are related to the electric and magnetic field transforms. Thus, both near field and far-field solutions can be evaluated. The far fields scattered by the irregular layered structure can be evaluated in closed form in terms of the field transforms by using steepest descent techniques.

## 2 Research Objectives

1. Determine the full wave like and cross polarized fields scattered by irregular layered structures.
2. Determine the full wave like and cross polarized differential scattering cross sections for irregular layered structures.
3. Determine realistic physical models of the nonspecular reflection and transmission scattering phenomena in layered media. The objective of this phase of the work is to synthesize scattering in complex stratified media from fundamental scattering matrix components.
4. Examine the effects of random rough interfaces with different surface height spectral density functions on the scattered fields.
5. Examine the effects of varying the complex permittivity, permeability and thickness of an intermediate layer in the stratified medium.
6. Examine the suitability of using the "effective dielectric coefficient" and "effective surface impedance" approximations.
7. One of the principal objectives of this research program is to coordinate with researchers at the laboratory facilities of the Chemical Research Development and Engineering Center (CRDEC) a series of experiments that are driven by the analytical results based on the full wave approach.
8. A second major objective of these investigations is to develop computer codes to evaluate the like and cross polarized scattered fields and cross sections using the full wave approach.

In addition to Progress Reports, the Scientific Program Officers were provided with preprints/reprints of Publications (see Section 3) and the computer programs were loaded on CRDEC's computer at the Aberdeen Proving Grounds.

### 3 List of Publications

#### 3.1 Papers Presented at Technical Meetings

1. 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 23-27, 1986. "Co-Polarized and Cross-Polarized Incoherent Diffuse Specific Intensities for Linearly Polarized Extinction of Irregular Shaped Particles."
2. 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 23-27, 1986. "Excitation Cross Sections and Albedos for Particles with Very Rough Surfaces."
3. 1986 International IEEE-AFS-Symposium and National Radio Science Meeting, University of Pennsylvania, Philadelphia, PA, June 9-13, 1986. "Interpretation of Backscatter Cross Sections for Normal Incidence Using Unified and Two-Scale Full Wave Analysis of Rough Surfaces."
4. 1986 International Union of Radio Science, Commission F Symposium on Wave Propagation: Remote Sensing and Communications, University of New Hampshire, Durham, NH, July 28-August 1, 1986. "Scattering and Depolarization of Linearly Polarized Waves by Finitely Conducting Particles of Irregular Shape."
5. International Union of Radio Science (URSI) Symposium on Electromagnetic Theory, Budapest, Hungary, August 25-29, 1986. "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity."
6. 20<sup>th</sup> Midwest Symposium on Circuits and Systems, University of Nebraska, Lincoln, NE, August 11-12, 1986. "Application of Full Wave Theory to Computer Aided Geometric Design."
7. Fall 1986 Electromagnetic Wave Propagation Panel Symposium on "Terrestrial Propagation Characteristics on Modern Systems of Communications Surveillance, Guidance and Control," sponsored by Advisory Group for Aerospace Research and Development (NATO), Ottawa, Canada, October 20-24, 1986. "Scattering and Depolarization by Rough Terrain and Vegetation Covered Terrain - Unified Full Wave Approach."
8. International Union of Radio Sciences (URSI) Meeting at the University of Colorado, Boulder, CO, January 12-15, 1987. "Scattering and Depolarization by Layers of Particles with Rough Surfaces Excited at Oblique Incidence."

9. U.S. Army Research Office Workshop on "Propagation in Random Media, Scattering from Rough Surfaces," Washington, D.C., March 23-25, 1987. Invited speaker on "Scattering from Random Rough Surfaces and Random Media Consisting of Irregular Shaped Particles."
10. Spring 1987 Electromagnetic Wave Propagation Panel Specialists' Meeting on Scattering and Propagation in Random Media sponsored by Advisory Group for Aerospace Research and Development (NATO), Rome, Italy, May 18-22, 1987. "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation."
11. 1987 IEEE AP-S International Symposium and URSI Radio Science Meeting, Virginia Tech, Blacksburg, VA, June 15-19, 1987. "Enhancement of Backscatter from Random Rough Surfaces - Full Wave Solution."
12. 1987 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 22-26, 1987. "Backscatter Enhancement of Infrared and Optical Radiation from Finitely Conducting Particles with Smooth and Very Rough Surfaces - First Order and Multiple Scatter."
13. XIIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, August 24-September 2, 1987. "Radar Cross Section of Rough Terrain and Vegetation Covered Terrain." Member of U.S. National Research Council Delegation.
14. International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, CO, January 5-8, 1988. "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces" with M. A. Fitzwater.
15. 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, FL, April 4-8, 1988. "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment" with M. A. Fitzwater.
16. 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse University, Syracuse, NY, June 6-11, 1988. "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."

17. 1988 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 20-24, 1988. "Non Specular Scattering by Irregular Layered Media - Full Wave Approach."
18. International Geoscience and Remote Sensing Symposium, Edinburgh University, Edinburgh, United Kingdom, September 13-16, 1988. "The Incoherent Like and Cross Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," (FRA- 211), 1988.
19. International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988. Invited paper "Stokes Parameters for Propagation Media with Random Distributions of Irregular Shaped Particles."
20. International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988. Invited paper "Scattering, Depolarization and Enhanced Backscatter from Random Rough Surfaces."
21. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 4-6, 1989. "Full-Wave Copolarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater.
22. IEEE AP-S International Symposium and URSI Radio Science Meeting, San Jose, CA, June 26-30, 1989. "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media."
23. 1989 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 26-30, 1989. "Transmission Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions," with G. Huang.
24. International Geoscience and Remote Sensing Symposium and International Radio Science Meeting, Vancouver, Canada, July 10-14, 1989. "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces Unified Full Wave Approach," with R. D. Kubik.
25. International Geoscience and Remote Sensing Symposium and International Radio Science Meeting, Vancouver, Canada, July 10-14, 1989. "Interpretation of the Apollo Lunar Surface Data Using the Unified Full Wave and the Two Scale Full Wave Approach," with M. Haugland.

26. Progress in Electromagnetic Research Symposium, MIT, Cambridge, MA, July 25-26, 1989. "Diffuse Specific Intensities and Backscatter Enhancement for Random Distribution of Finitely Conducting Particles with Rough Surfaces."
27. Progress in Electromagnetic Research Symposium, MIT, Cambridge, MA, July 25-26, 1989. "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths."
28. URSI International Symposium on Electromagnetic Theory at the Royal Institute of Technology, Stockholm, Sweden, August 14-17, 1989. "Physical Models of Nonspecular Scattering in Irregular Stratified Media."
29. International Union of Radio Science Commission F Symposium on Radio and Nonionized Media at La Londe-les-Maures, France, September 11-15, 1989. "Synthetic Aperture Radar Polarimetric Images for Swell and Ship Wakes - Full Wave Approach," with R. D. Kubik.
30. National Science Foundation Workshop on Future Directions in Electromagnetic Research, Panel member on Scattering and Inverse Scattering Techniques, July 27, 1989, Boston, MA. Invited paper on Electromagnetic Scattering by Randomly Rough Boundaries.
31. U.S. Army Research Chemical Research Development and Engineering Center, Aberdeen, MD, August 3, 1989. "Statistics for Identifying a Contaminated Rough Surface by Polarized IR Scattering: Full Wave Approach," with S. M. Haugland and A. H. Carrieri.
32. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 3-5, 1990. "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solution," with G. Huang.
33. International Union of Radio Science (URSI) (Commission F), Conference on Signature Problems in Microwave Remote Sensing of the Surface of the Earth, Hyannis, MA, May 16-18, 1990. "Remote Sensing of the Sea Surface Contaminated by Monomolecular Oil Slick - Full Wave Approach," with R. D. Kubik.
34. 1990 International Geoscience and Remote Sensing Symposium (IGARSS '90) Symposium on Remote Sensing Science for the Nineties and International Radio Science Meeting, University of Maryland, College Park, MD, May 20-24, 1990. "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscatter Radar Cross Sections - Full Wave Approach," with Y. F. Li.

35. IEEE AP-S International Symposium and URSI Radio Science Meeting, Dallas, TX, May 7-11, 1990, "Full Wave Multiple Scattering from Rough Surfaces" with M. El-Shenawee.
36. 1990 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 25-28, 1990, "Multiple Scattering of Electromagnetic Waves from Coated Rough Surfaces," with S. M. Haugland.
37. XXIII<sup>d</sup> General Assembly of the International Union of Radio Science, Prague, Czechoslovakia, August 28-September 5, 1990, Invited paper, "Radiowave Propagation over Terrain Characterized by a Broad Range of Roughness Scales and Varying Electromagnetic Parameters."
38. International Union of Radio Science Symposium on Scattering from Random Media (Joint Session B/F), Prague, Czechoslovakia, August 28-September 5, 1990, "Like and Cross Polarized Backscatter Enhancement and Antispecular Transmission from Finitely Conducting Two Dimensionally Rough Surfaces."
39. Advisory Group for Aerospace Research and Development, Fall 1990, Electromagnetic Wave Propagation Panel Symposium on Use or Reduction of Propagation and Noise Effects in Distributed Military Systems, Greece, October 15-19, 1990, "Utilization or Reduction of the Effects of Sea Clutter for Real and Synthetic Aperture Polarimetric Radars."
40. The Fourth Biennial IEEE Conference on Electromagnetic Field Computation, Toronto, Canada, October 22-24, 1990, "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Coated Rough Surfaces," with M. El-Shenawee.
41. 1990 U.S. Army Chemical Research Development and Engineering Center Scientific Conference on Chemical Defense Research, Aberdeen, MD, November 13-16, 1990, "Computation of Mueller Matrix Elements for Irregular Stratified Media - Full Wave Approach," with S. M. Haugland and A.H. Carrieri.
42. International Geoscience and Remote Sensing Symposium, and International Radio Science Meeting, Espoo, Finland, June 3, 1991, "Full Wave Solutions for Mueller Matrix Elements Used to Remotely Sense Irregular Stratified Structures," with S. M. Haugland.
43. International Geoscience and Remote Sensing Symposium, and Radio Science Meeting, Espoo, Finland, June 3, 1991, "High Resolution Radar Polarimetric Imaging of the Ocean Surface Due to Tilt Modulation - Unified Full Wave Approach," with R. D. Kubik.

44. IEEE-AP-S International Symposium and URSI Radio Science Meeting, London, Ontario, Canada, June 24-28, 1991, "Single and Multiple Scatter and Depolarization from Two Dimensional Rough Surfaces," with M. El-Shenawee.
45. 1991 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 24-28, 1991, "Mueller Matrix Elements for Optically Thin Chemical Coating Layers Over Rough Surfaces," with S. M. Haugland and A. H. Carrieri.
46. Progress in Electromagnetic Research Symposium, MIT, Cambridge, MA, July 1-5, 1991, "Two-Dimensional Random Rough Surfaces that Exhibit Uniform Enhanced Backscatter for V and H Polarizations Over a Very Wide Range of Incident Angles," with R. D. Kubik.
47. Topical Meeting of the International Commission for Optics, Atmospheric, Volume and Surface Scattering and Propagation, Florence, Italy, August 27-30, 1991, "Single and Multiple Scatter from Random Rough Surfaces, Full Wave Solutions," with R. D. Kubik and M. El-Shenawee.
48. Advisory Group for Aerospace Research and Development, Fall 1991, Electromagnetic Wave Propagation Panel Symposium on Remote Sensing of the Propagation Environment, Cesme, Turkey, September 30 - October 4, 1991, "Active Remote Sensing of the Ionosphere and the Earth Surface Irregularities."
49. International Union of Radio Science (URSI) Meeting, University of Colorado, Boulder, CO, January 7-11, 1992, "Diffuse Incoherent Radar Group Cross Sections for Random Rough Surfaces with Height-Slope Correlations, Included."
50. Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, Boulder, CO, 14-16 January 1992, "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments, Unified Full Wave Approach," with R. D. Kubik.
51. 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92) and International Radio Science Meeting, Houston, TX, May 26-29, 1992, "Unified Full Wave Solution for the Scattering Cross Sections of the Rough Sea Surface Coated with a Thin Film," with R. D. Kubik.

52. 1992 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, MD, June 22-25, 1992, "Use of a New Polarimetric Optical Bistatic Scatterometer to Measure the Transmission and Reflection Mueller Matrix for Arbitrary Incident and Scatter Direction."
53. Nasoscope User Conference, Santa Barbara, CA, June 24-27, 1991, 1991 Digital Instruments, "Surface Characterization for Random Rough Surface Scattering Theories and Oxygen Plasma Ashing Effects on Al and Ti Space Protective Coatings."
54. 1992 IEEE-APS International Symposium and URSI Radio Science Meeting, July 20-24, 1992, Chicago, IL, "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee.
55. URSI International Symposium on Electromagnetic Theory, Sydney, Australia, 17-20 August 1992, "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics."

### 3.2 Papers Published in Technical Literature

1. "Multiple Scattering in Media Consisting of Nonspherical Finitely Conducting Particles," with M. A. Fitzwater, *Proceedings of the 1985 CRDC Scientific Conference on Obscuration and Aerosol Research*, CRDEC-SP, pp. 1-9, 1986.
2. "Full Wave Solutions for Electromagnetic Scattering and Depolarization in Irregular Stratified Media," Special Issue of *Radio Science* on Waves in Inhomogeneous Media, Vol. 21, No. 4, pp. 543-550, July-August 1986.
3. "Scattering and Depolarization by Conducting Cylinders with Rough Surfaces," with M. A. Fitzwater, *Applied Optics*, Vol. 25, pp. 1826-1832, June 1986.
4. "Multiple Scattering by Conducting Particles with Random Surfaces at Infrared and Optical Frequencies," with M. A. Fitzwater, *Radio Science*, Vol. 21, No. 4, pp. 689-706, July-August 1986.
5. "Co-polarized and Cross-polarized Incoherent Diffuse Intensities Scattered by Finitely Conducting Particles of Irregular Shape," with M. A. Fitzwater, *Proceedings of the 1986 International Union of Radio Science Symposium on Wave Propagation and Remote Sensing*, Durham, NH, pp. 4.2.1-4.2.4, August 1986.
6. "Extinction Cross Sections and Albedos for Particles with Very Rough Surface," with S. Chakrabarti and M. A. Fitzwater, *Applied Optics*, Vol. 25, No. 15, pp. 2530-2536, August 1986.
7. "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity," with M. A. Fitzwater, *Proceedings of the International Radio Science Union Symposium on Electromagnetic Theory*, Budapest, Hungary, pp. 63-65, August 1986.
8. "Scattering and Depolarization of Linearly Polarized Waves by Finitely Conducting Particles of Irregular Shape," with M. A. Fitzwater, *Journal of Applied Physics*, Vol. 60, No. 6, pp. 2123-2132, September 1986.
9. "Co-Polarized and Cross-Polarized Incoherent Specific Intensities for Waves at Oblique Incidence upon Layers of Finitely Conducting Particles of Irregular Shape," with M. A. Fitzwater, *Journal of the Optical Society of America A*, Vol. 4, pp. 41-56, January 1987.

10. "Unified Full Wave Approach Applied to Scattering and Depolarization by Random Rough Surfaces - An Overview," *Journal of Wave-Material Interaction*, Vol. 2, No. 2, pp. 161-180, April 1987.
11. "Review of the Full Wave Solutions for Rough Surface Scattering and Depolarization - Comparisons with Geometric and Physical Optics, Perturbation and Two-Scale Solutions," *Journal of Geophysical Research*, Vol. 92, No. 65, pp. 5209-5224, May 15, 1987.
12. "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation," with M. A. Fitzwater, *Proceedings of the Advisory Group for Aerospace Research and Development (NATO) Spring 1987 Electromagnetic Wave Propagation Panel Symposium Scattering and Propagation in Random Media*, AGARD-CPP-419, pp. 12-1, 12-15, May 1987.
13. "Scattering and Depolarization by Random Rough Surfaces, Unified Full Wave Approach - An Overview," *Proceedings of the International Symposium on Multiple Scattering of Waves in Random Media and Random Rough Surfaces*, eds. V.V. Varadan and V.K. Varadan, pp. 715-733, Pennsylvania State University, 1987.
14. "Albedos and Extinction Cross Sections for Particles with Very Rough Surfaces," with S. Chakrabarti and M. A. Fitzwater, *Proceedings of the 1986 CRDC Scientific Conference on Obscuration and Aerosol Research*, CRDEC-SP, pp. 1-14, 1987.
15. "Co-Polarized and Cross-Polarized Incoherent Diffuse Specific Intensities for Linearly Polarized Excitation of Irregular Shaped Particles," with M. A. Fitzwater, *Proceedings of the 1986 CRDC Scientific Conference on Obscuration and Aerosol Research*, CRDEC-SP, pp. 1-14, 1987.
16. "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater, *Optics Communications*, Vol. 63, No. 6, pp. 355-360, September 1987.
17. "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity," with M. A. Fitzwater, invited paper in special issue of *Radio Science*, Vol. 22 No. 6, pp. 889-898, November 1987.

18. "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M. A. Fitzwater, *Journal of the Optical Society of America A*, Vol. 5, pp. 89-98, January 1988.
19. "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, *Proceedings of the SPIE 1988 Technical Symposium on Wave Propagation and Scattering in Varied Media*, Vol. 927, pp. 78-87, April 6-8, 1988.
20. "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater *Journal of Wave-Material Interaction*, Vol. 3, No. 3, pp. 173-187, April 1988.
21. "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater *Journal of Wave-Material Interaction*, Vol. 3, No. 3, pp. 199-218, July 1988.
22. "Comparison of Unified Full-Wave Solutions for Normal-Incidence Microwave Backscatter from Sea with Physical Optics and Hybrid Solutions," with D. E. Barrick and M. A. Fitzwater, *International Journal of Remote Sensing*, Vol. 9, No. 3, pp. 365-377, 1988.
23. "Backscatter Enhancement of Infrared and Optical Radiation from Finitely Conducting Particles with Smooth and Very Rough Surfaces - First Order and Multiple Scatter," with M. A. Fitzwater, *Proceedings of the 1987 Scientific Conference on Obscuration and Aerosol Research* CRDEC-SP-88031, pp. 619-630, 1988.
24. "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media," *Radio Science*, Vol. 23, No. 5, pp. 749-759, September-October 1988.
25. "Full Wave - Co-Polarized Non Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, *Journal of the Optical Society of America, A* Vol. 5, pp. 1873-1882, November 1988.
26. "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M. A. Fitzwater, *Journal of the Optical Society of America A*, Vol. 6, pp. 33-43, January 1989.

27. "The Incoherent Like- and Cross-Polarized Backscatter Cross Sections of an Anisotropic Rough Sea Surface with Swell," with C. M. Herzinger and M. A. Fitzwater, *Journal of Geophysical Research - Oceans*, Vol. 94, No. C2, pp. 2159-2169, February 1989.
28. "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces: Unified Full Wave Approach," with R. D. Kubik, *Proceedings of the IGARSS '89 Conference on Remote Sensing*, Vancouver, Canada, IEEE #89CH2768-0, Vol. 3, pp. 1292-1295, July 10-14, 1989.
29. "Interpretation of the Apollo Lunar Surface Data Using the Unified and the Two Scale Full Wave Approach," with M. Haugland, *Proceedings of the IGARSS '89 Conference on Remote Sensing*, Vancouver, Canada, IEEE, #89CH2768-0, Vol. 3, pp. 1296-1299, July 10-14, 1989.
30. "Electromagnetic Wave Scattering by Randomly Rough Boundaries," Invited paper on Review in Progress and Emerging Future Directions - Scattering and Inverse Scattering Techniques Panel, *Proceedings of the National Science Foundation Workshop on Future Direction in Electromagnetic Research*, Boston, MA, pp. 311-314, July 29, 1989.
31. "Scattering Cross Sections and Backscatter Enhancement for Two Dimensional Rough Surfaces with Different Correlation Lengths," *Proceedings of Progress in Electromagnetic Research Symposium*, Boston, MA, pp. 146-147, July 1989.
32. "Diffuse Specific Intensities and Backscatter Enhancement from Random Distributions of Finitely Conducting Particles with Rough Surfaces," *Proceedings of Progress in Electromagnetic Research Symposium*, Boston, MA, pp. 398-399, July 1989.
33. "Physical Models of Nonspecular Scattering in Irregular Stratified Media," *Proceeding of the 1989 Union of the International Radio Science Symposium on Electromagnetic Theory*, Stockholm, Sweden, pp. 503-505, August 14-17, 1989.
34. "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater *IEEE Transactions on Antennas and Propagation*, AP-S Vol. 37, No. 12, pp. 1609-1616, December 1989.
35. "Non Specular Scattering by Irregular Layered Media," *Proceedings of the 1988 Scientific Conference on Obscuration and Aerosol Research*, 1990.

36. "Full Wave Multiple Scattering from Rough Surfaces," with M. El-Shenawee, *Proceeding of the IEEE AP-S International Symposium and URSI Radio Science Meeting*, Dallas, TX, Vol. IV, pp. 1548-1551, May 1990.
37. "Statistical Characterization of Random Rough Surfaces Using the Tilt Modulation of the Backscattered Radar Cross Section - Full Wave Approach," with Y. F. Li, *Proceedings of the International Geoscience and Remote Sensing Symposium*, Vol. II, pp. 1401-1403, May 1990.
38. "Electromagnetic Scattering and Depolarization Across Rough Surfaces - Full Wave Solutions," with G. Huang, *Proceedings of the 1989 Scientific Conference on Obscuration and Aerosol Research*, 1990.
39. "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee, *Proceedings of the Fourth Biennial IEEE Conference on Electromagnetic Field Computation AP-S*, Toronto, Ontario Canada, October 24, 1990.
40. "Computation of Mueller Matrix Elements of Stratified Media," with S. M. Haugland and A. H. Carrieri, *Proceedings of the 1990 Scientific Conference on Chemical Defense*, November 1990.
41. "Single and Multiple Scatter and Depolarization from Two-Dimensional Rough Surfaces," with M. El-Shenawee, *Proceedings of the IEEE 1991 International Symposium AP-S*, London, Ontario, Canada, June 24-28, 1991.
42. "Polarized IR Scattering Used to Identify Contaminant Coatings over Rough Surfaces," *Proceedings of the 1991 Scientific Conference on Obscuration and Aerosol Research*, in press, June 1991.
43. "Use of Supercomputers to Evaluate Singly and Multiply Scattered Electromagnetic Fields from Rough Surfaces," with M. El-Shenawee, *IEEE Trans. on Magnetics*, Vol. 27, No. 5, pp. 4287-4290, September 1991.
44. "High Resolution Radar Polarimetric imaging of the Ocean Surface Due to Tile Modulation - Unified Full Wave Approach," with R. D. Kubik, *Proceedings of IGARSS'91 on Remote Sensing: Global Monitoring for Earth Management*, Espoo, Finland, Vol. 1, p. 2017-2020, 1991.

45. "Full Wave Solutions for Mueller Matrix Elements Used to Remotely Sense Irregular Stratified Structures," with S. Haugland, and A. Carrieri, *Proceedings of IGARSS'91 on Remote Sensing: Global Monitoring for Earth Management*, Espoo, Finland, Vol. 1, p. 1479-1482, 1991.
46. "Multiple Scattering of Electromagnetic Waves from Coated Rough Surfaces," with S. M. Haugland, *Proceedings of the 1990 Scientific Conference on Obscuration and Aerosol Research*, 1991.
47. "Full Wave Analysis for Rough Surface Diffuse, Incoherent Radar Cross Sections with Height-Slope Correlations Included," *IEEE Trans. on Antennas and Propagation*, Vol. 39, No. 9, pp. 1293-2304, September 1991.
48. "Scattering Cross Sections of Non-Gaussian Rough Surfaces: Unified Full Wave Approach," with Y. F. Li, *IEEE Transactions on Antennas and Propagation*, Vol. 39, No. 12, pp. 1777-1781, December 1991.
49. "Remote Sensing of Monomolecular Oil Slicks Characterized by Rough Surface Spectra Obtained in Controlled Experiments: Unified Full Wave Approach," with R. D. Kubik, *Proceedings of the Specialist Meeting on Microwave Radiometry and Remote Sensing Applications*, June 1992.
50. "Irregular Media Effects on Radiowave Signals Used in Navigation and Positioning Signals," *Proceedings of the Advisory Group on Aerospace Research and Development (AGARD) Electromagnetic Wave Propagation Panel, 50<sup>th</sup> Symposium on Radio Location Techniques*, June 1992.
51. "Unified Full Wave Solution for the Scattering Cross Sections of the Rough Sea Surface Coated with a Thin Film of Oil," with R. D. Kubik, *Proceedings of the 1992 International Geoscience and Remote Sensing Symposium (IGARSS'92) and International Radio Science Meeting*, June 1992.
52. "Identification of Contaminant Coatings Over Rough Surfaces Using Polarized IR Scattering," with S. M. Haugland and A.H. Carrieri, *Applied Optics*, Vol. 31, No. 19, pp. 3847-3852, July 1, 1992.

53. "Multiple Scattering from Random Distribution of Individual Rough Surface Scatterers," with M. El-Shenawee, *Proceedings of the 1992 Antennas and Propagation Society International Symposium*, in press July 1992.
54. "Transformation of Rice's Small Perturbation Results for Rough Surface Scattering into a Comprehensive Single Scatter Solution that Includes Physical and Geometrical Optics," *Proceedings of the 1992 International Union of Radio Science (URSI) Symposium on Electromagnetic Theory*, Sydney, Australia, August 1992.

#### **4 Scientific Personnel Associated with this Project and Degrees Awarded During this Reporting Period**

Professor Ezekiel Bahar was the Principal Investigator and Dr. M.A. Fitzwater was a Research Associate for the first two years.

M.S. degrees were awarded to Guorong Huang and S.M. Haugland. R.D. Kubik is nearing the completion on his Ph.D. degree requirements and T. Guminski is nearing the completion of his M.S. degree requirements.

M.S. Thesis by Guorong Huang completed May 1990, titled, "Transmission Scattering and Depolarization of Electromagnetic Waves Across Rough Interfaces Full Wave Approach."

M.S. Thesis by S.M. Haugland completed May 1991, titled, "Scattering of Electromagnetic Waves From Coated Rough Surfaces."

T. Guminski (expected graduation Summer 1993), Title of M.S. Thesis: "Scattering from Surfaces with Non-Gaussian Statistics."

R.D. Kubik (expected graduation Summer 1993), Title of Ph.D. Dissertation: "Scattering and Depolarization upon Transmission and Reflection from Multilayered Structures."

During the period June 12, 1986 and September 30, 1988, Robert Frickel was the Scientific Program Officer. The Scientific Program Officer during the period of contract renewal October 1, 1988 and April 12, 1992 was Dr. A. Carrieri.

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## APPENDIX

### SEMI-ANNUAL PROGRESS REPORTS

PROGRESS REPORT #1

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 12 June 1986 - 11 September 1986
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator

Principal Investigator  
Dr. Ezekiel Bahar  
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Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
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Attention: SMCCR-RSP-B  
APG, MD 21010-5423

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers Presented at Technical Meetings

- (i) 1986 International IEEE/AFS-Symposium and National Radio Science Meeting, University of Pennsylvania, Philadelphia, Pennsylvania, June 9-13, "Interpretation of Backscatter Cross Sections for Normal Incidence Using Unified and Two-Scale Full Wave Analysis of Rough Surfaces."
- (ii) 1986 International Union of Radio Science, Commission F Symposium on Wave Propagation: Remote Sensing and Communications, University of New Hampshire, Durham, New Hampshire, July 28-August 1, 1986, "Scattering and Depolarization of Linearly Polarized Waves by Finitely Conducting Particles of Irregular Shape."
- (iii) International Union of Radio Science (URSI) Symposium on Electromagnetics Theory, Budapest, Hungary, August 25-29, 1986, "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity."
- (iv) 1986 International Geoscience and Remote Sensing Symposium (IGARSS '86) University of Zurich-Irchel, Switzerland, September 8-11, 1986, "SEASAT Microwave Altimeter Measurement of the Ocean Gravity-Wave Equilibrium-Range Spectral Behavior Using Full Wave Theory."
- (v) 20th Midwest Symposium on Circuits and Systems, University of Nebraska-Lincoln, August 11-12, 1986, "Application of Full Wave Theory to Computer Aided Geometric Design."
- (vi) 1986 CRDC Scientific Conference on Obscuration and Aerosol Research Aberdeen, Maryland, June 23-27, 1986, "Co-Polarized and Cross-Polarized Incoherent Diffuse Specific Intensities for Linearly Polarized Excitations of Irregular Shaped Particles."
- (vii) 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 23-27, 1986, "Extinction Cross Sections and Albedos for Particles with Very Rough Surfaces."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Interpretation of Backscatter Cross Sections for Normal Incidence Using Unified and Two-Scale Full Wave Analysis of Rough Surfaces," with D. E. Barrick and M. A. Fitzwater, submitted for review.

(7.3) Papers Accepted for Publication

- (i) "Scattering and Depolarization by Random Rough Surfaces, Unified Full Wave Approach - An Overview," Wave Material Interaction -- in press (September 1986).

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Scattering and Depolarization by Conducting Cylinders with Rough Surfaces," with M. A. Fitzwater, Applied Optics, Vol. 129, pp. 1826-1832, June 1986.
- (ii) "Full Wave Solutions for Electromagnetic Scattering and Depolarization in Irregular Stratified Media," Special Issue of Radio Science on Waves in Inhomogeneous Media, Vol. 21, No. 4, pp. 543-550, July-August 1986.

- (iii) "Multiple Scattering by Irregular Shaped Particles of Finite Conductivity at Infrared and Optical Frequencies," with M. A. Fitzwater, Radio Science, Vol. 21, No. 4, pp. 689-706, July-August 1986.
- (iv) "Co-Polarized and Cross-Polarized Incoherent Diffuse Intensities Scattered by Finitely Conducting Particles of Irregular Shape," Proceedings of the 1986 International Union of Radio Science Symposium on Wave Propagation and Remote Sensing, Durham, New Hampshire, pp. 4.2.1-4.2.4, August 1986.
- (v) "Extinction Cross Sections and Albedos for Particles with Very Rough Surface," with S. Chakrabarti and M. A. Fitzwater, Applied Optics, Vol. 25, No. 15, pp. 2530-2536, August 1986.
- (vi) "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity," with M. A. Fitzwater, Proceedings of the International Radio Science Union Symposium on Electromagnetic Theory, Budapest, Hungary, pp. 63-65, August 1986.

## OUTLINE OF RESEARCH FINDINGS

The electromagnetic fields scattered by irregular stratified media consisting of three layers characterized by complex permittivities  $\epsilon_n$  and permeabilities  $\mu_n$  ( $n=0,1,2$ ) (see Fig. 1) were derived. The interface between media 0 and 1 is the planar surface  $y=0$  while the interface between media 1 and 2 is the rough surface  $y=h(x)$  where  $h(x)$  is either a deterministic or random function of the variable  $x$ . The electromagnetic sources are assumed to be magnetic or electric line sources  $\bar{J}_m$  and  $\bar{J}_e$  parallel to the  $z$  axis. These sources excite vertically (V), and horizontally (H) polarized waves respectively with respect to the interface  $y=0$ . The line sources are assumed to be at large distances from the surface  $y=0$ , thus the incident waves are assumed to be plane waves in the direction

$$\bar{n}^i = \sin\theta_o^i \bar{a}_x - \cos\theta_o^i \bar{a}_y \equiv S_o^i \bar{a}_x - C_o^i \bar{a}_y \quad (1)$$

Complex time harmonic excitations  $\exp(i\omega t)$  are assumed throughout this work. Since this problem is two dimensional, the direction of the scattered waves is given by

$$\bar{n}^f = \sin\theta_o^f \bar{a}_x + \cos\theta_o^f \bar{a}_y \equiv S_o^f \bar{a}_x + C_o^f \bar{a}_y \quad (2)$$

The approximate surface impedance  $Z_s$  (admittance  $Y_s$ ) is also used to characterize the medium  $y < h(x)$  and the expressions for the scattered fields are compared with the corresponding expressions for the three media problem.

The observation point  $(x,y)$  is assumed to be very far from the surface  $y=0$  ( $k_o(x^2+y^2)^{1/2} \equiv k_o\rho \gg 1$ ), therefore only the scattered radiation fields are considered in this work.

The electric (e) and magnetic (m)  $z$  directed line source  $\bar{J}_\ell$  of intensity  $I_\ell$  ( $\ell=e,m$ ) can be expressed as follows in terms of the Dirac delta functions  $\delta(\cdot)$ ;

$$\bar{J}_\ell = I_\ell \delta(x-x_o) (y-y_o) \bar{a}_z \quad (3)$$

in which  $k_o(x_o^2 + y_o^2)^{1/2} = k_o\rho_o \gg 1$ .

Using the full wave approach, it can be shown that the scattered vertically (V) and horizontally (H) polarized waves can be expressed in terms of their  $z$  directed magnetic and electric fields respectively (Bahar 1973a,b).

The corresponding scattered electric and magnetic fields are

$$\bar{E}^{Vf} = \eta_o H_z^f \bar{a}_z \times \bar{n}^f, \quad \bar{H}^{Hf} = \bar{n}^f \times E_z^f \bar{a}_z / \eta_o \quad (4)$$

in which

$$\eta_n = \sqrt{\mu_n / \epsilon_n} \quad (n=0,1,2) \quad (5)$$

is the intrinsic impedance for medium  $n$ . The  $z$  component of the scattered fields can be expressed as follows in matrix form

$$G^f = G_o S G^i \quad (6)$$

where the coefficient  $G_o$  is

$$G_o = \left( \frac{1}{2\pi k_o \rho_o} \right)^{1/2} \exp(i\pi/4) \exp(-ik_o \rho_o) \quad (7)$$

in which

$$k_n = \omega(\mu_n \epsilon_n)^{1/2} \quad (8)$$

is the wavenumber for medium  $n=0,1,2$ .

The amplitude of the incident  $z$  directed magnetic or electric field at the origin is

$$G_\ell^i = -\frac{1}{2} \left( \frac{1}{2\pi k_o \rho_o} \right)^{1/2} \exp(i\pi/4) \exp(-k_o \rho_o) \cdot \begin{cases} \omega \epsilon_o I_m \\ \omega \mu_o I_e \end{cases} \quad (9)$$

in which  $G_\ell^i$  is the element of the  $2 \times 1$  column matrix

$$G^i = \begin{bmatrix} G_m^i \\ G_e^i \end{bmatrix} \equiv \begin{bmatrix} H_z^i \\ E_z^i \end{bmatrix} \quad (10)$$

Similarly,  $G^f$  is a  $2 \times 1$  column matrix with elements  $G_\ell^f$  equal to the  $z$  component of the scattered magnetic and electric fields

$$G^f = \begin{bmatrix} G_m^f \\ G_e^f \end{bmatrix} \equiv \begin{bmatrix} H_z^f \\ E_z^f \end{bmatrix} \quad (11)$$

The elements of the scattering matrix  $S$  are  $S^{PQ}(P, Q=V \text{ or } H)$ . In view of the two dimensional nature of the problem, the scattered waves are not depolarized and

$$S^{VH} = S^{HV} = 0 \quad (12)$$

and  $S$  is a diagonal matrix

$$S = \begin{bmatrix} S^{VV} & 0 \\ 0 & S^{HH} \end{bmatrix} \quad (13)$$

The diagonal terms can be expressed as follows:

$$S^{PP} = S_{oo}^{PP} I_{oo} + S_{11}^{PP} \sum_{p=1}^{\infty} \sum_{q=1}^{\infty} I_{pq}^{PP} \quad (14)$$

in which the first term represents scattering due to the interface  $y=0$  only and the double summation (over  $p$  and  $q$ ) represents multiple scattering in the intermediate layer ( $0 \geq y \geq h(x)$  and  $-L \leq x \leq L$ ).

$$S_{00}^{VV}(\theta^f, \theta^i) = \frac{2c_o^f c_o^i \{[(\mu_1/\mu_o)c_1^f c_1^i - s_o^f s_o^i][1 - (\epsilon_o/\epsilon_1)] + [1 - (\mu_1/\mu_o)]\}}{[c_o^f + c_1^f(\eta_1/\eta_o)][c_o^i + c_1^i(\eta_1/\eta_o)][c_o^f + c_o^i]} \quad (15)$$

where in accordance to Snell's law:

$$k_o s_o^i = k_n \sin \theta_n^i \equiv k_n s_n^i \text{ and } k_o s_o^f = k_n \sin \theta_n^f \equiv k_n s_n^f \quad (16a)$$

and

$$c_n^i = [1 - (s_n^i)^2]^{\frac{1}{2}}, \quad c_n^f = [1 - (s_n^f)^2]^{\frac{1}{2}}, \quad \text{Im}(c_n^i) \geq 0, \quad \text{Im}(c_n^f) \geq 0 \quad (16b)$$

Furthermore

$$I_{oo} = \int_{-L}^L \exp[ik_o(s_o^f - s_o^i)x] k_o dx = 2k_o L \text{sinc } k_o(s_o^f - s_o^i)L \quad (17)$$

where  $\text{sinc}(\alpha) = \sin(\alpha)/\alpha$ . For  $p \geq 1$  and  $q \geq 1$

$$S_{pq}^{VV}(\theta^f, \theta^i) = \frac{2c_1^f c_1^i \{[(\mu_2/\mu_1)c_2^f c_2^i - s_1^f s_1^i][1 - (\epsilon_1/\epsilon_2)] + [1 - (\mu_2/\mu_1)]\}}{[c_1^f + c_2^f(\eta_2/\eta_1)][c_1^i + c_2^i(\eta_2/\eta_1)][c_1^f + c_1^i]} \cdot T_{1o}^V(\theta^f) T_{1o}^V(\theta^i) \eta_1/\eta_o \quad (18)$$

and

$$I_{pq}^{VV} = \frac{[R_{o1}^V(\theta^f) R_{21}^V(\theta^f)]^{p-1} [R_{o1}^V(\theta^i) R_{21}^V(\theta^i)]^{q-1} [c_1^f + c_1^i]}{(2p-1)c_1^f + (2q-1)c_1^i} \cdot \int_{-L}^L \exp\{ik_1(s_1^f - s_1^i)x + ik_1[(2p-1)c_1^f + (2q-1)c_1^i]h(x)\} k_o dx \quad (19)$$

in which  $R_{o1}^V$  and  $R_{21}^V$  are the Fresnel reflection coefficients for vertically polarized waves incident from medium 1 to medium 0 and from medium 1 to medium 2 respectively. The transmission coefficient  $T_{1o}^V$  is for vertically polarized waves incident from medium 0 to medium 1. When the approximate impedance boundary condition is used at the interface  $y=h(x)$  instead of the exact two media boundary conditions  $S_{pq}^{VV}$  in (18) is given by

$$S_{pq}^{VV} = \frac{2c_1^i c_1^f (1 - s_1^f s_1^i - z_s^2)}{(c_1^f + z_s)(c_1^i + z_s)(c_1^f + c_1^i)} T_{1o}^V(\theta^f) T_{1o}^V(\theta^i) \eta_1/\eta_o \quad (20)$$

in which  $z_s$  is the normalized surface impedance

$$z_s = Z_s/\eta_1 = \eta_2/\eta_1 \quad (21)$$

For scattering in the specular direction ( $\theta^f = \theta^i$ )

$$S_{oo}^{VV}(\theta^i, \theta^i) = 2C_o^i R_{1o}^V(\theta^i) \quad (22)$$

and

$$S_{pq}^{VV}(\theta^i, \theta^i) = 2C_1^i R_{21}^V(\theta^i) T_{1o}^V(\theta^i) T_{1o}^V(\theta^i) \eta_1 / \eta_o \quad (23)$$

The above full wave solutions for the scattered radiation fields satisfy the reciprocity and duality relationships in electromagnetic theory. They should not be confused with a geometric or physical optics solution to the problem Schlak and Wait (1968). The corresponding scattering coefficients for the horizontally polarized waves  $S_{pq}^{HH}$  can be obtained directly for the above expressions for  $S_{pq}^{VV}$  on interchanging the permittivity  $\epsilon$  with the permeability  $\mu$  and the surface impedance  $z_s$  with its reciprocal; surface admittance  $y_s$ .

#### References

1. Bahar, E. (1973a), "Electromagnetic Wave Propagation in Inhomogeneous Multilayered Structures of Arbitrarily Varying Thickness-Generalized Field Transforms," J. Math. Phys., Vol. 14, No. 8, pp. 1024-1029.
2. Bahar, E. (1973b), "Electromagnetic Wave Propagation in Inhomogeneous Multilayered Structures of Arbitrarily Varying Thickness--Full Wave Solutions," J. Math. Phys., Vol. 14, No. 8, pp. 1030-1036.
3. Schlak, G. A., and J. R. Wait, (1968), "Attenuation Function for Propagation Over a Non-Parallel Stratified Ground," Can. J. Phys., Vol. 46, pp. 1135-1136.

PROGRESS REPORT #2

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 12 September 1986 - 31 December 1986
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator  
Dr. M. A. Fitzwater - Research Associate

Principal Investigator  
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University of Nebraska  
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Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers Presented at Technical Meetings

- (i) Fall 1986 Electromagnetic Wave Propagation Panel Symposium on "Terrestrial Propagation Characteristics on Modern Systems of Communications Surveillance, Guidance and Control," Sponsored by Advisory Group for Aerospace Research and Development (NATO), Ottawa, Canada, October 20-24, 1986, "Scattering and Depolarization by Rough Terrain and Vegetation Covered Terrain-- Unified Full Wave Approach."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Computer Aided Graphics for Three Dimensional Objects Based on Full Wave Theory," (with S. Chakrabarti) submitted for review.
- (ii) "Review of the Full Wave Solutions for Rough Surface Scattering and Depolarization - Comparisons with Geometric and Physical Optics Perturbation and Two-Scale Solutions," submitted for review.

(7.3) Papers Accepted for Publication

- (i) "Co-Polarized and Cross-Polarized Incoherent Specific Intensities for Waves at Oblique Incidence Upon Layers of Finitely Conducting Particles of Irregular Shape," Journal of the Optical Society of America, in press.
- (ii) "Application of Full Wave Theory to Computer Aided Geometric Design," (with S. Chakrabarti), Proceedings of the 29th Midwest Symposium on Circuits and Systems, in press.
- (iii) "Albedos and Extinction Cross Sections for Particles with Very Rough Surfaces," with S. Chakrabarti and M. A. Fitzwater, Proceedings of the 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, in press.
- (iv) "Co-Polarized and Cross-Polarized Incoherent Diffuse Specific Intensities for Linearly Polarized Excitation of Irregular Shaped Particles," with M. A. Fitzwater, Proceedings of the 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, in press.
- (v) "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity," Invited paper in Special Issue of Radio Science - in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Scattering and Depolarization of Linearly Polarized Waves by Finitely Conducting Particles of Irregular Shape," with M. A. Fitzwater, Journal of Applied Physics, Vol. 60, No. 6, pp. 2123-2132, September 1986.
- (ii) "SEASAT Microwave Altimeter Measurement of the Ocean Gravity-Wave Equilibrium-Range Spectral Behavior Using Full Wave Theory," Proceedings of the 1986 International Geoscience and Remote Sensing Symposium, IGARSS 1986, Zurich, ESA, SP-254, pp. 1345-1349, September, 1986.
- (iii) "Scattering and Depolarization by Random Rough Terrain and Vegetation Covered Terrain - Unified Full Wave Approach," Proceedings of the Advisory Group for Aerospace Research and Development (NATO) on Terrestrial Propagation Characteristics in Modern Systems of Communications, Surveillance, Guidance and Control, AGARD-CPP-407, pp. 4.1-4.14, October 1986.

## OUTLINE OF RESEARCH FINDINGS

Computer codes were developed to evaluate the scattered vertically and horizontally polarized fields for irregular layered media (See Report #1) Medium 1 ( $0 < y < h$ ) is represented by the permittivity of a thin film of liquid while medium 2 is represented by the permittivity of foilage or a painted metal surface. Both the solutions for the three media problem as well as the solution involving the approximate impedance boundary condition are considered. The convergence of the series expansion of the solution was studied for dissipative and non-dissipative media. Special attention is given to the determination of the effects of the thin liquid film covering the rough surface of the substratum  $y > h$ . (See Fig. 1).

During the following reporting periods the following analytical and numerical work will be done:

- (i) Transformation to a local coordinate system will be used to account for the slopes of the rough interface  $y=h(x)$ .
- (ii) Special consideration will be given to random rough surfaces.
- (iii) Solutions for the coherent and incoherent scattered powers will be derived.
- (iv) Additional work will be done to more closely represent the permittivities of the liquid film and the substratum.
- (v) Generalization of the analytical results to three dimensional scattering problems including depolarization: (a) Point sources, (b) Three dimensional incident and scattered wave normals  $\vec{n}^i$  and  $\vec{n}^s$ , (c) Two dimensionally rough surfaces  $h(x,z)$ .

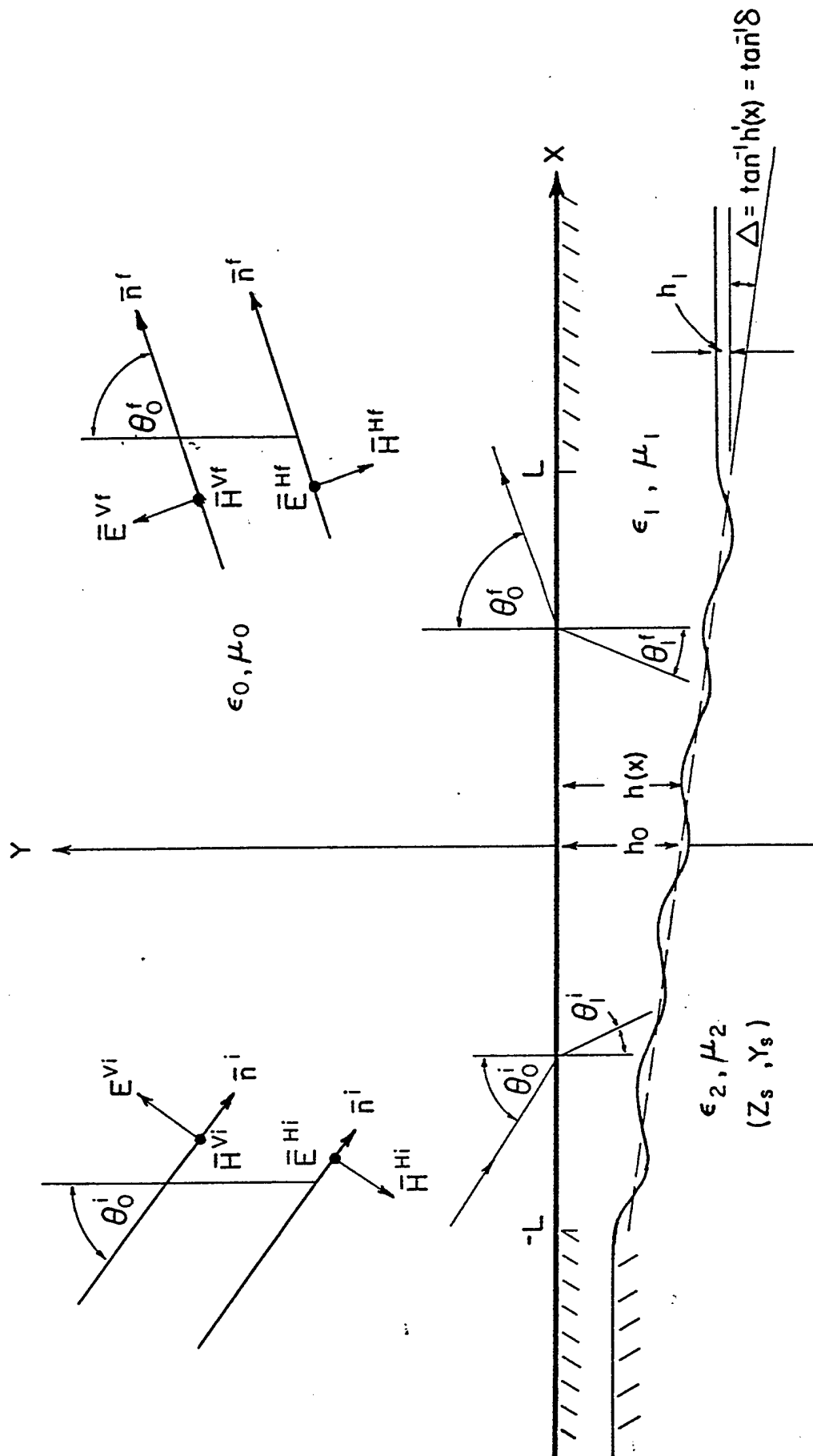


Fig. 1. Electromagnetic Wave Scattering from Irregular Layered Media.

PROGRESS REPORT #3

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 January 1987 - 31 March 1987
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:  
  
See Attached List
8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator

Dr. M. A. Fitzwater - Research Associate

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Robert Frickel  
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APG, MD 21010-5423

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES;

(7.1) Papers Presented at Technical Meetings

- (i) International Union of Radio Sciences (URSI) Meeting at the University of Colorado, Boulder, January 12-15, 1987, "Scattering and Depolarization by Layers of Particles with Rough Surfaces Excited at Oblique Incidence."
- (ii) U.S. Army Research Office Workshop on "Propagation in Random Media, Scattering from Rough Surfaces" - March 23-25, 1987 Washington, D.C., Invited speaker on "Scattering from Rough Surfaces and Random Media consisting of Irregular Shaped Particles."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Comparison of Unified Full-Wave Solutions for Normal-Incidence Microwave Backscatter from Sea with Physical Optics and Hybrid Solutions" with D.E. Barrick and M.A. Fitzwater, submitted for review.
- (ii) "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation", with M.A. Fitzwater, Proceedings of the Advisory Group for Aerospace Research and Development (NATO) Spring 1987 Electromagnetic Wave Propagation Panel Symposium "Scattering and Propagation in Random Media", submitted for review.
- (iii) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces", with M.A. Fitzwater, submitted for review.
- (iv) "Application of Full Wave Theory to Scattering and Depolarization by Random Rough Surfaces From Which Optical Backscattering Enhancement Has Been Observed in Controlled Laboratory Experiments", with M.A. Fitzwater, submitted for review.
- (v) "Use of the Full Wave Approach to Demonstrate the Respective Regions of Validity of the Perturbation, Physical Optics and Hybrid Solutions for Electromagnetic Scattering by Random Rough Surfaces", submitted for review.

(7.3) Papers Accepted for Publication

- (i) "Computer Aided Graphics for Three Dimensional Objects Based on Full Wave Theory", (with S. Chakrabarti) IEEE Computer Graphics and Applications, in press.
- (ii) "Review of the Full Wave Solutions for Rough Surface Scattering and Depolarization - Comparisons with Geometric and Physical Optics, Perturbation and Two-Scale Solutions", Journal of Geophysical Research, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Scattering and Depolarization by Random Rough Surfaces, Unified Full Wave Approach - An Overview," Proceedings of the International Symposium on Multiple Scattering of Waves in Random Media and Random Rough Surfaces, Editors V.V. Varadan and V.K. Varadan, pp. 715-733, Pennsylvania State University, 1987.

(7.4) Papers Published in the Technical Literature and Submitted with This Report, cont.

- (ii) "Co-Polarized and Cross-Polarized Incoherent Specific Intensities for Waves at Oblique Incidence Upon Layers of Finitely Conducting Particles of Irregular Shape", Journal of the Optical Society of America A, Vol. 4, pp. 41-56, January 1987.
- (iii) "Application of Full Wave Theory to Computer Aided Geometric Design" (with S. Chakrabarti), Proceedings of the 29th Midwest Symposium on Circuits and Systems, Editor, M. Ismail, pp. 911-915, North Holland, NY 1987.

## OUTLINE OF RESEARCH FINDINGS

During this reporting period (January 1-March 31, 1987) the principal investigator presented two papers at technical meetings and submitted five papers to professional/technical journals for review. Two papers were accepted for publication and three papers were published in the Professional/Technical literature (see Item #7 and enclosures).

Additional work was done on the development of computer codes to evaluate the vertically and horizontally polarized waves scattered by irregular layered media (See Report #1). These codes are being tested at various frequencies of excitations for both dissipative and non-dissipative media. Particular attention is given to the electrical characteristics (complex permittivity) of the intermediate layer (medium 1, see Fig. 1) at optical and infrared frequencies. The effects of varying the thickness of this layer are also of special interest.

Progress is also being made with the analytical development of this research project as described in the Outline of Report #2. Thus, the transformation of the analytical results for media with deterministic rough interfaces to structures with random rough interfaces is being carefully studied.

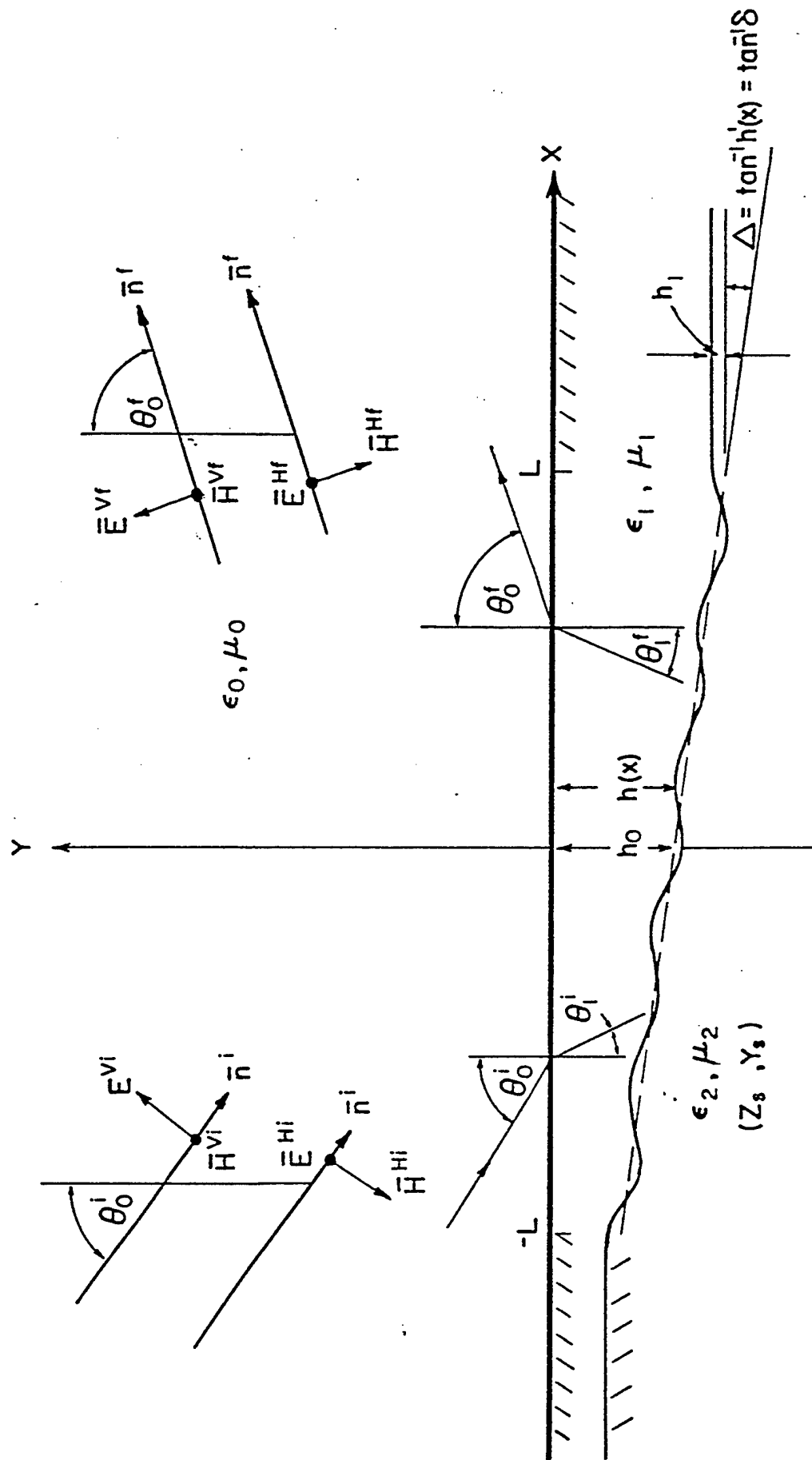


Fig. 1. Electromagnetic Wave Scattering from Irregular Layered Media.

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PROGRESS REPORT #4

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 April 1987 - 30 June 1987
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:  
  
See Attached List
8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator

Dr. M. A. Fitzwater - Research Associate

Principal Investigator  
Dr. Ezekiel Bahar  
University of Nebraska  
Department of Electrical Engineering  
Lincoln, NE 68588

Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers Presented at Technical Meetings

- (i) Spring 1987 Electromagnetic Wave Propagation Panel Specialist's Meeting on Scattering and Propagation in Random Media sponsored by Advisory Group for Aerospace Research and Development (NATO), Rome, Italy, May 18-22, 1987, "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation."
- (ii) 1987 IEEE AP-S International Symposium and URSI Radio Science Meeting, Virginia Tech., Blacksburg, Virginia, June 15-19, 1987, "Enhancement of Backscatter from Random Rough Surfaces-Full Wave Solution."
- (iii) 1987 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 22-26, 1987. "Backscatter Enhancement of Infrared and Optical Radiation from Finitely Conducting Particles with Smooth and Very Rough Surfaces--First Order and Multiple Scatter."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Physical Interpretation of the Full Wave Solutions for the Electromagnetic Fields Scattered from Irregular Stratified Media," attached to this report and submitted for review.

(7.3) Papers Accepted for Publication

- (i) "Comparison of Unified Full-Wave Solutions for Normal-Incidence Microwave Backscatter from Sea with Physical Optics and Hybrid Solutions," with D. E. Barrick and M. A. Fitzwater, International Journal of Remote Sensing, in press.
- (ii) "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation," with M. A. Fitzwater, Proceedings of the Advisory Group for Aerospace Research and Development (NATO) Spring 1987 Electromagnetic Wave Propagation Panel Symposium "Scattering and Propagation in Random Media," in press.
- (iii) "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater, Optics Communications, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Full Wave Theory Applied to Computer Aided Graphics for Three Dimensional Objects," (with S. Chakrabarti) IEEE Computer Graphics and Applications, Special Issue, Supercomputers for Graphics, Vol. 7, No. 7; July 1987, pp. 46-60.
- (ii) "Review of the Full Wave Solutions for Rough Surface Scattering and Depolarization - Comparisons with Geometric and Physical Optics, Perturbation and Two-Scale Solutions," Journal of Geophysical Research, Vol. 92, No. 65, pp. 5209-5224, May 15, 1987.

## OUTLINE OF RESEARCH FINDINGS

During this reporting period (April 1 - June 30, 1987), the principal investigator presented three papers at technical meetings and submitted one paper to professional/technical journals for review. Three papers were accepted for publication and two were published in the professional/technical literature (see Item #7 and enclosures).

Significant progress has been made on the physical interpretation of the full wave solutions for the electromagnetic fields scattered from irregular stratified media. The full wave solutions for the vertically and horizontally polarized electromagnetic fields scattered by irregular stratified media are expressed in terms of double infinite sums. These full wave solutions satisfy the reciprocity relationships in electromagnetic theory. The physical interpretation of each term in the double infinite series provides insights into the nonspecular scattering phenomena for irregular stratified media. It is shown that  $n+1$  different terms of the full wave expansion replace the single  $n$ th term of the corresponding geometric optics series (see Fig. 1). For scattering in the specular direction these  $n+1$  terms become analytically indistinguishable and the full wave solution reduces to the geometric optics solution. The full wave solutions are also consistent with Rice's perturbation solution for rough surface scattering in the low frequency limit. The physical interpretation of the full wave solutions which are based on complete spectral expansions of the fields could be used to construct solutions for the non-specularly scattered fields in complex problems involving irregular stratified media. Details of this work are presented in the attached manuscript (see Item #7.2(i) of this quarterly report).

For irregular stratified media it is necessary to consider both nonspecular reflection from rough surfaces as well as nonspecular transmission across rough surfaces. Specular transmission (analogous to specular reflection) corresponds to refraction of the incident wave across a plane interface in accordance with Snell's law. Progress has been made in obtaining the full wave solutions for scattering across rough interfaces. Details will be worked out during the next reporting period (July 1 - September 30, 1987).

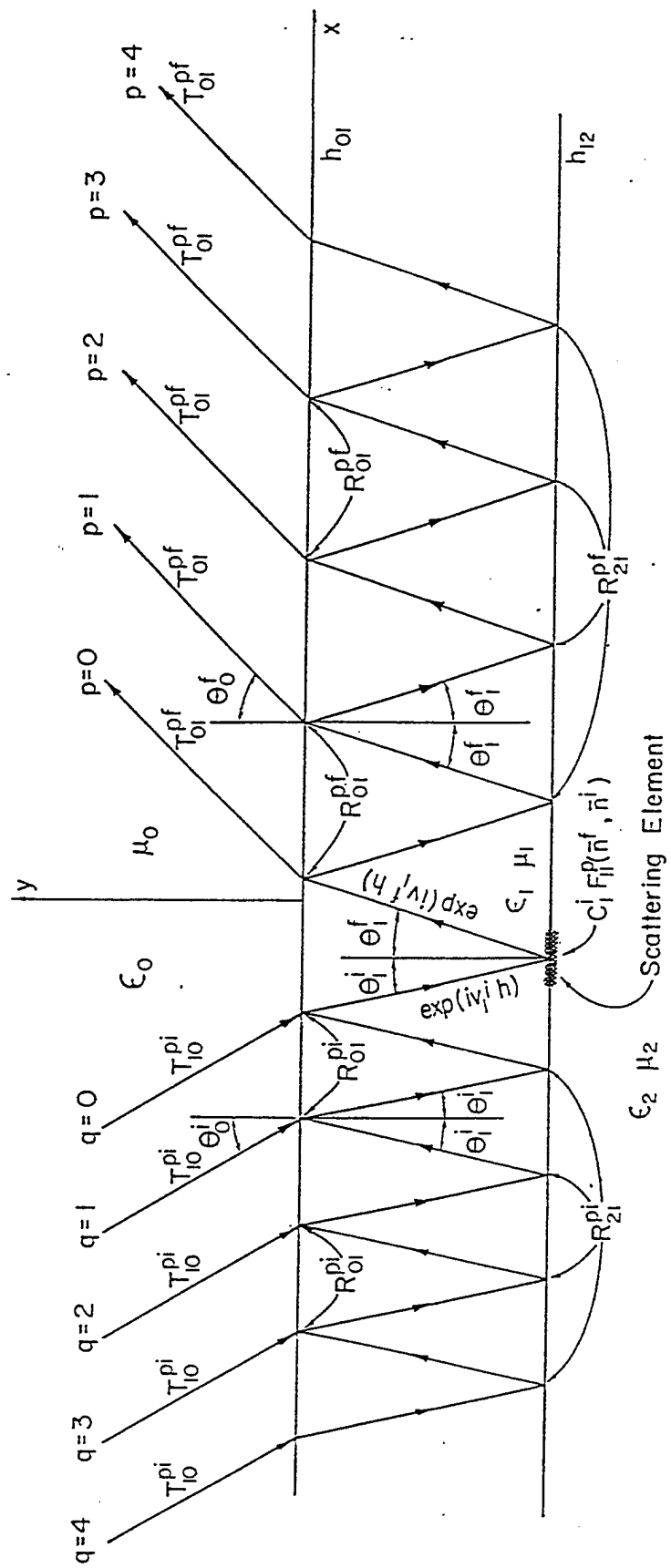


Fig 1

PROGRESS REPORT #5

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 July 1987 - 30 September 1987
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:  
  
See Attached List
8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator  
Dr. M. A. Fitzwater - Research Associate  
Undergraduate Research Assistants - Hourly

Principal Investigator  
Dr. Ezekiel Bahar  
University of Nebraska  
Department of Electrical Engineering  
Lincoln, NE 68588

Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers Presented at Technical Meetings

- (i) XXIIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, August 24 - September 2, 1987, "Radar Cross Section of Rough Terrain and Vegetation Covered Terrain." Member of U.S. National Research Council Delegation.

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Full Wave - Co-Polarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M. A. Fitzwater, submitted for review.
- (ii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M. A. Fitzwater, submitted for review.
- (iii) "Backscatter Enhancement of Infrared and Optical Radiation from Finitely Conducting Particles with Smooth and Very Rough Surfaces - First Order and Multiple Scatter," with M. A. Fitzwater, Proceedings of the 1987 Scientific Conference on Obscuration and Aerosol Research.
- (iv) "Unified Full Wave Approach Applied to Scattering and Depolarization by Random Rough Surfaces - An Overview," Journal of Wave-Material Interaction.

(7.3) Papers Accepted for Publication

- (i) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Full Wave Theory and Controlled Optical Experiments for Enhanced Scattering and Depolarization by Random Rough Surfaces," with M. A. Fitzwater, Optics Communications, Vol. 63, No. 6, pp. 355-360, Sept. 1987.
- (ii) "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation," with M. A. Fitzwater, Proceedings of the Advisory Group for Aerospace Research and Development (NATO) Spring 1987 Electromagnetic Wave Propagation Panel Symposium  
"Scattering and Propagation in Random Media," AGARD-CPP-419, pp. 12-1, 12-15.

## Outline of Research Findings

During the reporting period (July 1 - September 30, 1987), the principal investigator presented an invited paper at the XXII General Assembly of the International Union of Radio Science on "Radar Cross Section of Rough Terrain and Vegetation Covered Terrain." See Item (7.1)(i). The principal investigator was an official U.S. delegate appointed by the U.S. National Research Council.

Four technical/scientific manuscripts were prepared and submitted for publication--see Item (7.2)(i)-(iv) (preprint of Item (7.2)(i) enclosed).

One paper was accepted for publication by the Journal of the Optical Society of America--see Item (7.3)(i).

Two papers were published in the professional/technical literature--See Item (7.4)(i) and (ii) (reprints enclosed).

Electromagnetic waves in irregular layered media are scattered upon reflection as well as transmission across an interface. Full wave solutions were derived for the nonspecular diffuse scattering upon transmission across an irregular interface between two media. The solutions were shown to agree in the high frequency limit with the physical optics solutions (based on the Kirchhoff approximations of the surface fields) when scattering is primarily near-specular. It also agrees, in the low frequency limit with the perturbation solutions when the root mean square height of the rough surfaces is small compared to the wavelength of the electromagnetic wave and when the mean square slopes of the rough surface are small compared to unity. The full wave solutions are shown to satisfy the realizability, reciprocity and duality relationships in electromagnetic theory and they are invariant to coordinate transformations.

Thus using the full wave approach, the rough surface is characterized by a  $(2 \times 2)$  differential scattering matrix whose elements are the differential reflection and transmission scattering coefficients for an elementary surface element when the excitation is from above or below the surface element of the irregular interface (see Fig. 1). Details of this work are provided in the attached pre-print Item # (7.2)(i).

Significant progress is also being made on scattering upon reflection and transmission in irregular stratified media.. Details will be presented in Progress Report #6 (October 1-December 31, 1987).

A comprehensive proposal has been submitted to the sponsor of this research project for the extension of the current contract beyond its current expiration date in September 1988.

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PROGRESS REPORT #6

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 October 1987 - 31 December 1987
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:  
  
See Attached List
8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator  
Dr. M. A. Fitzwater - Research Associate  
Undergraduate Research Assistants - Hourly

Principal Investigator  
Dr. Ezekiel Bahar  
University of Nebraska  
Department of Electrical Engineering  
Lincoln, NE 68588

Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

## Outline of Research Findings

During the reporting period (October 1 - December 31, 1987), the principal investigator prepared two papers for publication and review (preprint of Item (7.2) (ii), enclosed). One paper was accepted for publication in the Journal of Wave Material Interaction - see Item (7.3) (i) and one paper was published in the professional/technical literature (see Item (7.4) (i), reprint enclosed). The principal investigator will present a paper on "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces" at the International Union of Radio Science NRC Meeting, University of Colorado, Boulder, January 5-8, 1988.

Significant progress has been made on scattering upon reflection and transmission in irregular stratified media (see Fig. 1). A physical interpretation is given to each term in the full wave expansion of the vertically or horizontally polarized electromagnetic fields scattered by irregular stratified media (see Fig. 2). These solutions provide a basis for the construction of physical models of nonspecular scatter in complex irregular layered structures. The full wave solutions involve a pair of nonspecular reflection scattering coefficients ( $F_{00}^P$  and  $F_{11}^P$ ) and a pair of nonspecular transmission scattering coefficients ( $F_{01}^P$  and  $F_{10}^P$ ) that reduce to the familiar Fresnel reflection and transmission coefficients for the specular case.

For the special case of parallel stratified media, the total solution expressed in terms of a single reflection term, two infinite sums as well as a double infinite sum, reduces to the closed form solution for reflection of electromagnetic waves from uniform layered media. The full wave solutions are shown to satisfy the reciprocity and duality relationships in electromagnetic theory and they are invariant to coordinate transformations. The relationships between the full wave solution and the high frequency physical optics solution and the low frequency perturbation solutions are also demonstrated. The analysis is relevant to problems of communication in irregular stratified media and to problems of remote sensing.

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1) Papers to be Presented at Technical Meetings

- (i) International Union of Radio Science (URSI) - NRC Meeting, University of Colorado, Boulder, Colorado, January 5-8, 1988, "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces--Theory and Experiment."
- (ii) "Full Wave Co-Polarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," - Revised.

(7.3) Papers Accepted for Publication

- (i) "Unified Full Wave Approach Applied to Scattering and Depolarization by Random Rough Surfaces--An Overview," Journal of Wave Material Interaction.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity," Radio Science, Vol. 22, No. 6, pp. 889-898, November 1987.

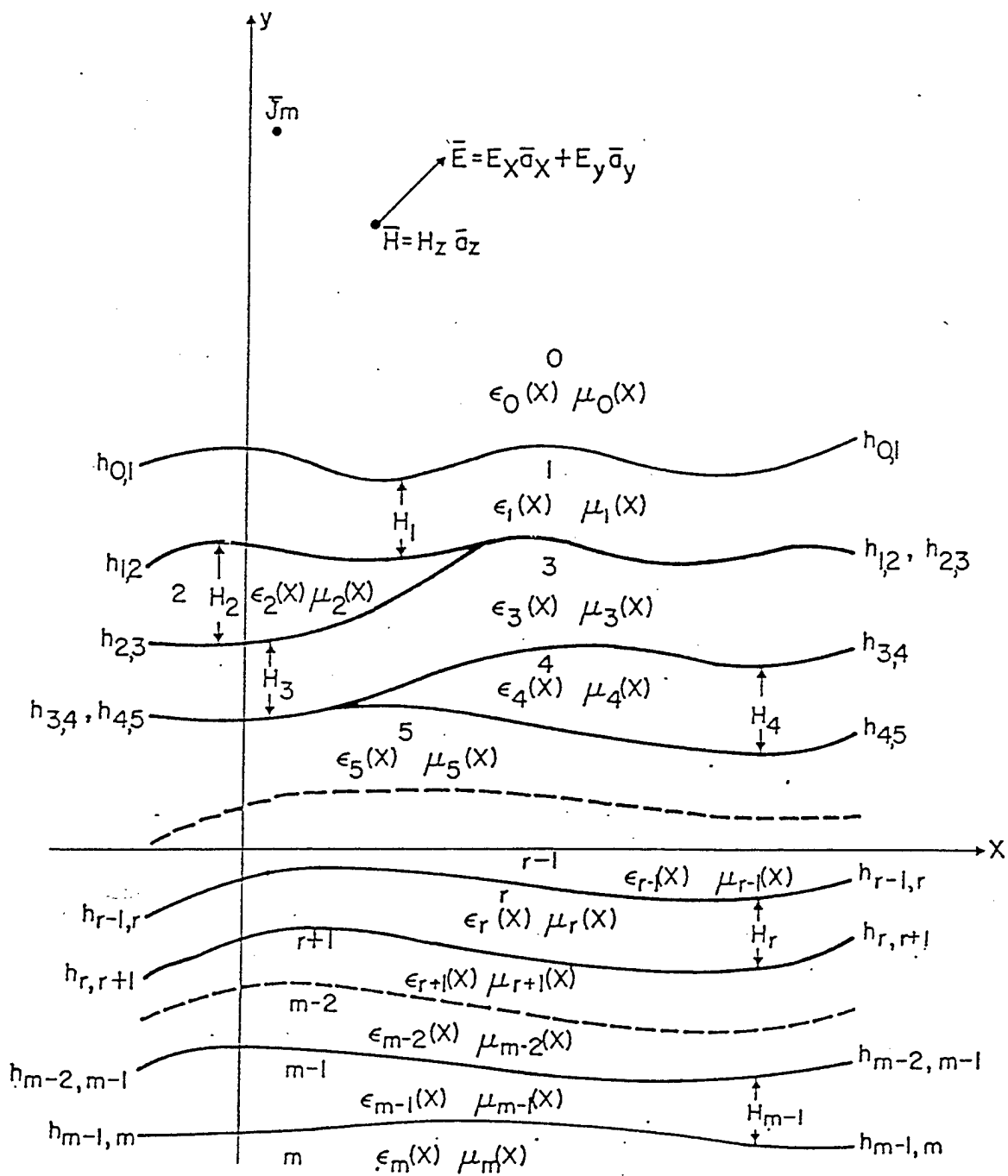
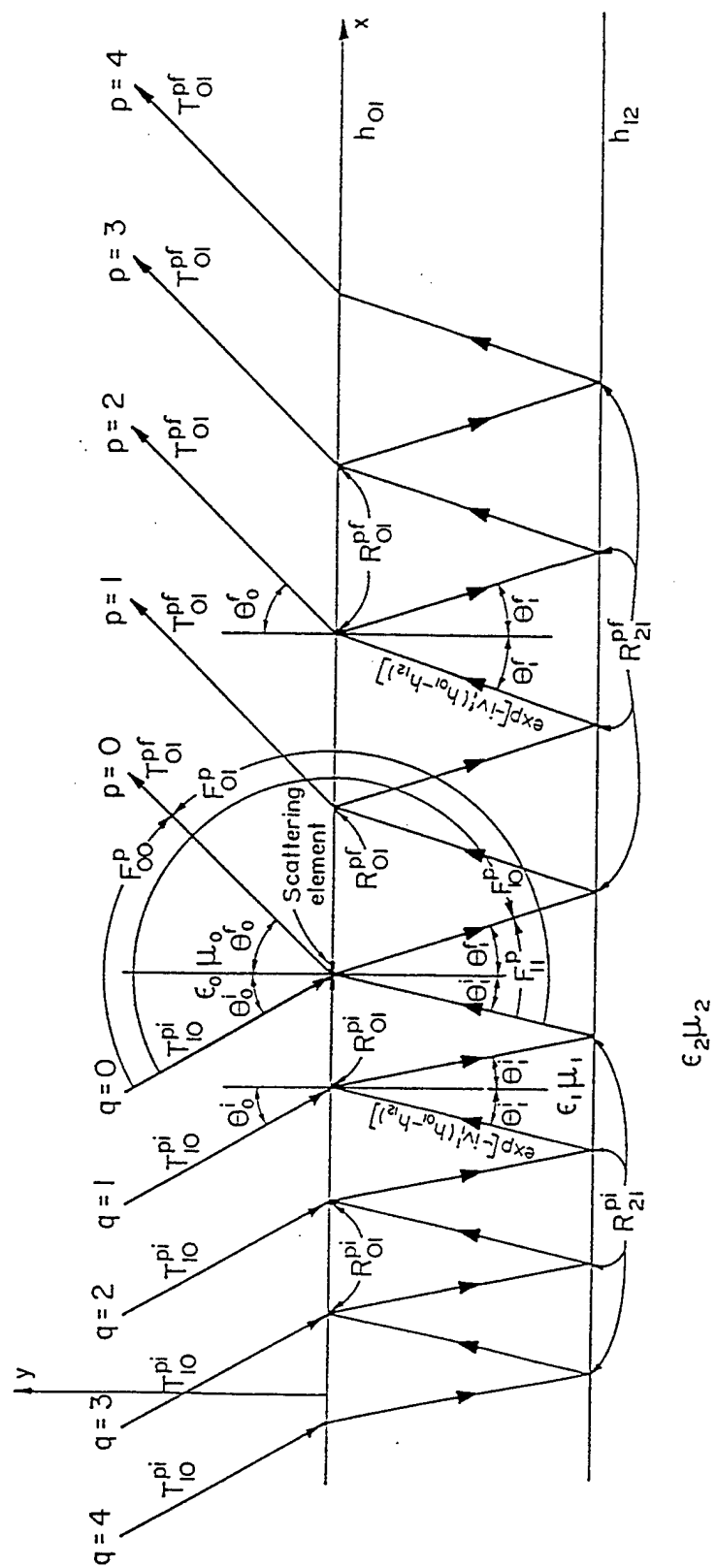


Fig. 1.



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PROGRESS REPORT #7

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 January 1988 - 31 March 1988
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:  
  
See Attached List
8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator  
Dr. M.A. Fitzwater - Research Associate  
Undergraduate Research Assistants - Hourly

Principal Investigator  
Dr. Ezekiel Bahar  
University of Nebraska  
Department of Electrical Engineering  
Lincoln, NE 68588

Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

### Outline of Research Findings

During the reporting period (January 1 - March 31, 1988), the principal investigator presented a paper on "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces" at the International Union of Radio Science NRC Meeting at the University of Colorado, Boulder, January 5-8, 1988 (see Item 7.1a). Three additional papers were accepted for presentation at Scientific Meetings (see Item 7.1b). The principal investigator prepared two papers for publication and review (see Item 7.2). One paper was accepted for publication (see Item 7.3) and one paper has been published in the professional/technical literature (see Item 7.4).

A complete analytical solution to the problem of electromagnetic propagation in irregular (three) layered media has been derived in terms of integrals over the nonplanar interfaces, between the different layers of the propagation media. The solutions obtained for the deterministic problem is currently being applied to problems in which the interfaces are characterized statistically by their joint surface height probability density functions. During the next reporting period (July 1988), a new graduate student will be assigned full time to develop computer codes to evaluate the radar cross sections for different irregular three layered propagation problems.

During this summer Mr. Craig Herzinger, a University of Nebraska-Lincoln graduate, will work with Dr. A. Carriere on the implementation of the computer codes (supplied by our research group to CRDEC) on their supercomputer. In the future, we plan to network directly (from Lincoln, Nebraska), with their computer facility.

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

- (i) International Union of Radio Science (URSI) - NRC Meeting, University of Colorado, Boulder, Colorado, January 5-8, 1988, "Backscatter Enhancement from Sparsely Distributed Large Particles with Rough Surfaces.

(7.1b) Papers Accepted for Presentation

- (i) 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, Florida, April 4-8, 1988, "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater.
- (ii) 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse University, Syracuse, N.Y., June 6-11, 1988, "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."
- (iii) 1988 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 20-24, 1988, "Non-Specular Scattering by Irregular Layered Media--Full Wave Approach."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors.
- (ii) "Scattering Cross Sections for Two-Dimensionally Rough Surfaces with Different Correlation Lengths."
- (iii) "Depolarization and Backscatter Enhancement in Light Scattering from Random Rough Surfaces - Theory and Experiment," with M.A. Fitzwater, submitted for review. (Revised).

(7.3) Papers Accepted for Publication

- (i) "Full Wave - Co-Polarized Non-Specular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces," with M.A. Fitzwater, Journal of the Optical Society of America A, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Multiple Scattering Effects of Random Distributions of Irregularly Shaped Particles on Infrared and Optical Propagation," with M.A. Fitzwater, Proceedings of the Advisory Group for Aerospace Research and Development (NATO) Spring 1987 Electromagnetic Wave Propagation Panel Symposium "Scattering and Propagation in Random Media," AGARD-CPP-419, pp. 12-1, 12-15, May 1987.

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PROGRESS REPORT #8

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 April 1988 - 30 June 1988
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator  
Dr. M.A. Fitzwater - Research Associate  
Mr. Guorong Huang - Graduate Student

Principal Investigator  
Dr. Ezekiel Bahar  
University of Nebraska  
Department of Electrical Engineering  
Lincoln, NE 68588

Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

## Outline of Research Findings

During the reporting period (April 1 - June 30, 1988), the principal investigator presented three papers at Scientific/Technical Meetings (see Item 7.1a). Two additional papers were invited for presentation at the International Working Group Meeting on Wave Propagation in Random Media (see Item 7.1b). Two papers were submitted for review (see Item 7.2) and two papers were accepted for publication in Scientific/Technical Journals. One paper on Enhancement of Backscattered Diffuse Specific Intensities has been published in the Journal of the Optical Society of America (see Item 7.4). A reprint of this article is attached to this report.

In order to apply the full wave analysis of electromagnetic scattering in irregular (three) layered media to three dimensional problems, closed form expressions are derived for the co- and cross-polarized transmission scattering coefficients at a rough interface. Since this phase of the analysis accounts for coupling between the vertically and horizontally polarized waves, more realistic models of irregular multilayered media can be analyzed using the full wave approach. The full wave approach is shown to satisfy the duality and reciprocity relations in electromagnetic theory. This analysis can be used to evaluate the co-polarized and cross-polarized scattering cross sections as well as all the elements of the Stokes Matrix.

Mr. Craig Herzinger, a University of Nebraska Graduate, is currently working with Dr. A. Carriere at the CRDEC on the computation of the Stokes Matrix for random rough surfaces. The results of these computations will be used to determine the elements of the Stokes Matrix that are most sensitive to variations in the rough surfaces parameters.

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

- (i) 1988 SPIE Technical Symposium on Optics, Electro-Optics and Sensors - Wave Propagation and Scattering in Varied Media, Orlando, Florida, April 4-8, 1988, "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater.
- (ii) 1988 IEEE AP-S International Symposium and URSI Radio Science Meeting, Syracuse University, Syracuse, N.Y., June 6-11, 1988, "Conditions for Coalescence of the Full Wave Solution for Rough Surface EM Scattering with Perturbation and Physical Optics Solutions in the Low and High Frequency Limits - Theory and Experiment."
- (iii) 1988 CRDEC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 20-24, 1988, "Non-Specular Scattering by Irregular Layered Media--Full Wave Approach."

(7.1b) Papers Accepted for Presentation

- (i) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988. "Stokes Parameters for Propagation Media with Random Distributions of Irregular Shaped Particles."
- (ii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988, "Scattering, Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(7.2) Papers Submitted for Review by Journal Editors

- (i) "Bistatic Incoherent Scattering Cross Sections for Two-dimensional Random Rough Surfaces of Finite Conductivity," with M. A. Fitzwater.
- (ii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M.A. Fitzwater, IEEE Transactions on Antennas and Propagation, Revised.

(7.3) Papers Accepted for Publication

- (i) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M. A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors, in press.
- (ii) "Scattering Cross Sections for Two-Dimensional Rough Surfaces with Different Correlation Lengths," with M. A. Fitzwater, Journal of Wave-Material Interaction, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Enhancement of the Backscattered Diffuse Specific Intensities from Random Distributions of Finitely Conducting Particles with Rough Surfaces," with M. A. Fitzwater, Journal of the Optical Society of America, A, Vol. 5, pp. 89-98, Jan. 1988.

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PROGRESS REPORT #9

1. PROJECT NUMBER: FI6VF6J2FINF
2. PERIOD COVERED BY REPORT: 1 July 1988 - 30 September 1988
3. TITLE OF PROPOSAL: Scattering and Depolarization by Irregular  
Layered Media--Full Wave Solutions
4. CONTRACT OR GRANT NUMBER: DAAA15-86-K-0023/P00001
5. NAME OF INSTITUTION: University of Nebraska-Lincoln
6. AUTHOR(S) OF REPORT: Ezekiel Bahar
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED  
DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

See Attached List

8. SCIENTIFIC PERSONNEL ASSOCIATED WITH THIS PROJECT AND DEGREES AWARDED  
DURING THIS REPORTING PERIOD:

Professor Ezekiel Bahar - Principal Investigator  
Dr. M.A. Fitzwater - Research Associate  
Mr. Guorong Huang - Graduate Student

Principal Investigator  
Dr. Ezekiel Bahar  
University of Nebraska  
Department of Electrical Engineering  
Lincoln, NE 68588

Scientific Program Officer  
Robert Frickel  
CODE W 15QKN  
U.S. Army AMCCOM  
Attention: SMCCR-RSP-B  
APG, MD 21010-5423

## Outline of Research Findings

During the reporting period (July 1, 1988 - September 30, 1988), the principal investigator presented two (2) papers at Scientific/Technical Meetings (see Item 7.1a). A paper on nonspecular transmission and reflection at a rough interface has been accepted for presentation at the URSI Meeting in Boulder, Colorado (see Item 7.1b). One paper was submitted (Item 7.2) and two papers were accepted for publication in Scientific/Technical Journals (Item 7.3). Reprints of two papers that were published in the Journal of Wave-Material Interaction and in the Proceedings of the SPIE 1988 Technical Symposium (Item 7.4) are attached to this report.

Full wave expressions for the co-polarized and cross-polarized transmission scattering coefficients at a rough interface between two electromagnetic media ( $\epsilon, \mu$ ) have been derived for arbitrary incident and scatter directions. Thus the incident and scatter planes are not necessarily co-planar. When the mean square height and slopes of the rough surface are very small ( $k_0^2 \langle h^2 \rangle \ll 1, \sigma_s^2 \ll 1$ ) the expressions have been shown to be in agreement with the corresponding expressions obtained using the small perturbation analysis. These transmission scattering coefficients are used in the three-dimensional analysis of electromagnetic scattering by irregular layered media.

During the reporting period, Mr. Craig Herzinger installed a full wave computer code (in the CRDEC supercomputer) for the evaluation of the elements of the Stokes matrix for electromagnetic (including optical) backscatter from rough surfaces. Craig was commended by Dr. Arthur A. Carrieri for the software development and the graphical analysis of the Full Wave light scattering models (see enclosure).

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

(7.1a) Papers Presented at Technical Meetings

- (i) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-21, 1988. "Stokes Parameters for Propagation Media with Random Distributions of Irregular Shaped Particles."
- (ii) International Working Group Meeting on "Wave Propagation in Random Media," Tallin, USSR, September 19-23, 1988, "Scattering, Depolarization and Enhanced Backscatter from Random Rough Surfaces."

(7.1b) Papers Accepted for Presentation

- (i) International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, January 4-7, 1988, "Full Wave Co-Polarized Nonspecular Transmission and Reflection Scattering Matrix Elements for Rough Surfaces."

(7.2) Papers Submitted for Review by Journal Editors

- (i) Nonspecular Scattering by Irregular Layered Media--Full Wave Approach.

(7.3) Papers Accepted for Publication

- (i) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M.A. Fitzwater, Journal of Wave Material Interaction.
- (ii) "Full Wave Physical Models of Nonspecular Scattering in Irregular Stratified Media," with M.A. Fitzwater, IEEE Transactions on Antennas and Propagation, in press.

(7.4) Papers Published in the Technical Literature and Submitted with This Report

- (i) "Scattering and Depolarization by Two-Dimensional Random Rough Surfaces of Finite Conductivity - Theory and Experiment," with M.A. Fitzwater, Proceedings of the SPIE 1988 Technical Symposium on Optics, Electro-Optics, and Sensors, 927-17.
- (ii) "Bistatic Incoherent Scattering Cross Sections for Two-Dimensional Random Rough Surfaces of Finite Conductivity," with M.A. Fitzwater, Journal of Wave Material International, Vol. 3, No. 2. pp. 173-187, April 1988.